Transportation Research Part D 95 (2021) 102851

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Assessing road network resilience: An accessibility comparative analysis

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ARTICLE INFO

Keywords:
Transport and mobility infrastructure
Accessibility
Resilience
Complex network
Valencia (Spain) and Sardinia (Italy)

ABSTRACT

In this study, we measure the resilience of the road networks in two Mediterranean regions: Valencia (Spain) and Sardinia (Italy). We apply a framework that is able to monitor the deterioration in territorial accessibility of the two systems in response to the cumulative elimination of sections. Road sections are removed according to different elimination types: random order, deterministic order of criticality, and deterministic order in areas at high risk of flooding. The results show that the Sardinian network is more resilient than the Valencian network, despite its poorer quality. We demonstrate that the framework can integrate climate change considerations in the resilience assessment. As the framework identifies the most critical sections, the method can be adopted as a support system by transport planners and policy makers.

1. Introduction

The scientific literature and the public awareness of adaptation to climate change have revived interest in the assessment of resilience. The declarations in the latest reports of the Intergovernmental Panel on Climate Change (IPCC) clearly warn governments of the need to adequately anticipate and counteract the main effects of climate change on human settlements and infrastructures. Climate change is expected to produce intense and extreme phenomena with significant impacts on human settlements and transportation infrastructures. Failures in sections of these systems may result in the blockage of large parts of the transport network and cascading negative effects. A number of scientists have designed frameworks operationalizing the definition and assessment of concepts such as vulnerability, robustness and resilience in transport networks (Sarlas et al., 2020; Ortega et al., 2020; Jenelius et al., 2006). Wang et al. (2015) provide a threefold definition of the vulnerability of a transportation system: it is associated to circumstances, where even small incidents can cause fatal consequences on the transportation system; it concerns risk, i.e. the susceptibility to adverse events that result in a reduction of serviceability such as the possibility of using a given infrastructure feature; and it refers to the interplay between the likelihood of incidents and their consequences on the transportation system. Another key concept is robustness, which is defined as “the extent to which, under prespecified circumstances, [a transportation system] is able to maintain the function for which it was originally designed” (Snelder et al., 2012). The term robustness analysis has also been used in comparisons of different transport

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https://doi.org/10.1016/j.trd.2021.102851

networks (Sullivan et al., 2010, Jafino et al., 2020) Finally, Wan et al. (2018) define resilience “as the ability of a transportation system to absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and costs after being affected by disruptions”.

The term resilience has been developed gradually in the context of ecological systems, then applied to multiple fields in psychology, economics, engineering, etc. (Wan et al., 2018; Zhou et al., 2019). Unlike other similar concepts in sustainability assessment such as carrying capacity (Cohen, 1995) and ecological footprint (Rees, 1996), resilience thinking involves approaching the resolution of critical situations in the system through proactivity and by adapting to severe circumstances to maintain operativity (Folke, 2016; De Montis et al., 2019; Mattsson and Jenelius, 2015). Numerous definitions of the notion of resilience have been proposed in the literature on transport planning. According to the comprehensive literature review by Wan et al. (2018), there are four key points in the definitions of resilience adopted in the transportation field: (i) it is a term used to describe a sort of ability inherent in a system (or network), or to name a function that can measure the performance of this system against disturbance; (ii) most definitions show this to be a useful concept for addressing the performance of a system when facing abnormal conditions caused by disruptive events; (iii) a wide variety of verbs are used to describe the performance of a disrupted system (e.g. resist, absorb, maintain); and (iv) resilience can be regarded as the ability to cling to a stable condition or to move from one state of equilibrium to another.

Another concept related to resilience, and one that is widely used in the transport literature to study the performance of networks, is criticality. It is applied to describe the contribution of each infrastructure component to the system’s performance, and has also been called “vulnerability” in the literature (Jafino et al., 2020). According to Taylor et al. (2006), among others, the critical elements of a network are those whose loss produces the greatest effects on the system. Transport network criticality analysis orders or ranks the network components according to their relevance in the system, and has been reported as a useful framework for planners to prioritize interventions (Ortega et al., 2020; Jafino et al., 2020; Jafino, 2021).

In most of these approaches, transport systems are modelled as networks with arcs representing transport infrastructure sections and nodes representing intersections (Barthélemy, 2011; Crucitti et al., 2004). The literature on complex networks provides analysts with methods to monitor the residual reaction capacity while the system is simulated to undergo the cumulative elimination of nodes or arcs according to different patterns (Gao et al., 2015; Gutfraind, 2012; De Montis et al., 2019). Random elimination models accidental events occurring to the infrastructure (car accidents, structural collapses, etc.), while deterministic elimination recreates damage targeting highly critical elements (traffic jams in key central sections, fatal meteorological events affecting highly exposed infrastructure elements, etc.). Accessibility is a key variable for the efficiency of a transportation network, since it describes the ability to reach several destinations from a given spatial origin by overcoming a generalized cost deriving from the friction of moving in space and time. Accessibility can thus be used as a sentinel variable to monitor the efficiency of a transportation system (García-Palomares et al., 2018; Ortega et al., 2020). Resilience assessment frameworks often consider failure drivers in the form of climate change-induced meteorological events; a classic example is flooding, which causes transportation sections to become unavailable for a period ranging from a couple of hours to many days. Adaptation to climate change implies that the most critical sections are protected from flooding or other climate events, i.e. they are maintained properly operational even in the case of extreme events such as unprecedented rainfall (Wang et al., 2017). The resilience of a transportation system is thus context specific, as it depends on certain climatic, geographical, infrastructural and socio-institutional characteristics. However, a flexible resilience assessment framework, i.e. one that can compare two or more transportation networks under a unifying perspective, is an important tool for detecting and explaining the differences and recommending suitable *ad-hoc* counteractions.

The rationale of this paper revolves around the possibility of building a framework for the comparative assessment of resilience in transportation systems. We develop a multistage method to map the reaction of two transport systems to the damage produced by the cumulative loss of sections in terms of territorial accessibility due to significant perturbations caused by severe random and deterministic fatal attacks on the transportation sections. We stress that the hydrogeological risk, a major effect of climate change, is a major driver of potential loss of sections.

The aim of this paper is therefore to assess the resilience of two road networks in the Mediterranean regions of Sardinia in Italy and Valencia in Spain. We build a framework capable of measuring comparatively the robustness of the two transportation networks by monitoring the decline in overall territorial accessibility, while subjecting the systems to the elimination of their sections according to four patterns. A lower decline in accessibility *ceteris paribus* – i.e. with the same percentage of sections eliminated – indicates greater resilience. The types of elimination reflect a variety of determinants of section failure: sections are simulated to be removed randomly or deterministically. In the latter case, sections are cancelled based on the highest individual decline in accessibility due to potential damage from flooding. This framework for assessing resilience can give analysts and decision-makers an accurate indication of the most fragile sections of the road networks and serve as a basis for policy recommendations and suggestions for specific defensive and preventive actions.

The argument is developed as follows. In the next section we report on the state of transport network resilience assessment. In the third section we present the methodology used in this paper to assess the resilience of a road network by monitoring the decline in accessibility associated to the cumulative removal of infrastructure sections. Section 4 describes the case of the two regional road networks selected, and the fifth section applies the assessment framework to study the comparative resilience of the two systems. In the sixth section we discuss the most important findings, and in the last section we present the final conclusions of this paper with regard to the objectives formulated above, and offer recommendations for future research.

2. Transport network resilience assessment

Although the resilience of transportation networks has been widely assessed in qualitative terms, little work has been done on quantitative analysis (Gu et al., 2020a,b). According to Reggiani et al. (2015) and Knoop et al. (2012), the evaluation of resilience or robustness in transport systems – such as a road network – is problematic. Scholars have sought to contribute, and many have followed a similar approach based on the so-called "node-and-link-removal" simulations (Jenelius & Mattsson, 2012; Tang et al., 2020; Yang et al., 2020) to assess a chosen network measure (Taylor et al., 2006; Jenelius et al., 2006; Sohn, 2006; Knoop et al., 2008; Erath et al., 2009; Jenelius & Mattsson, 2012; Zhang et al., 2015; Bhatia et al., 2015), although using different metrics or models to evaluate the impacts. However, the increase in generalized cost, travel time or travel distance is a vital component in the assessment (Jenelius & Mattsson, 2012; Taylor & Susilawati, 2012). As examples of these studies, Freiria et al. (2015) propose a model to evaluate the most important roads in the network through the application of the biclustering technique, road performance measures and connectivity patterns. Li and Kim (2014) use a connectivity-based survivability measure to study the Beijing subway system. Jenelius and Mattsson (2012) simultaneously disable the set of links intersecting a cell into which the study area is divided. Xu et al. (2018) develop a set of network-based measures for characterizing the resilience of a transportation network in terms of its redundancy.

Some authors have taken into account the impacts of severe disruptions in road capacity and traffic allocation in their resilience evaluations. The effect of reduced capacity on total travel time could be considered an indicator of the vulnerability of a link (Knoop et al., 2012). In their approaches, Jenelius (2007) and Knoop et al. (2008) block each of the links in a traffic simulation programme. Tang and Heinimann (2018) propose a congestion resilience metric for urban roads. Scott et al. (2006) evaluate the critical importance of certain network links (in terms of the change in travel time) as a consequence of redirecting all the traffic in the system if that link becomes unusable. Calvert and Snelder (2018) base their methodology on volatility in traffic flow. Liu et al. (2009) compute travel costs from the total travel time incurred by all the vehicles in the system, with the stipulation that all demand must be met in each disruption scenario. Fan and Liu (2010) compute travel costs assuming that user equilibrium is fully achieved, and only penalize solutions containing unsatisfied demand. Miller-Hooks et al. (2012) study the inherent capacity of the network to cope with interruption through its topological and operational attributes, and the possible actions that can be taken in an intermodal freight transport network.

While the overriding concerns in studies of urban networks are traffic congestion and travel time, regional planning studies require the analysis of the socio-economic consequences of network performance. Accessibility measurements can provide these tools (Taylor & Susilawati, 2012). Jafino et al. (2021) believe the functionality of the transport service to be one of the dimensions to consider when calculating criticality, and can be studied in terms of connectivity, travel cost or accessibility (Jafino et al., 2021). Numerous studies have operationalized the application and measurement of accessibility, proposing several methods and indicators (see, among others, Geurs et al., 2015; Geurs and van Wee, 2004; Kelobonye et al., 2020; Sarlas et al., 2020). Changes in accessibility levels have often been used to study the effects of transport in the territory, i.e. economic productivity (Liu & Zhang, 2018), variations in population and jobs (Hiramatsu, 2018); the relevance of cities (Monzón et al., 2013), and territorial cohesion (Ortega et al., 2012). The concept of accessibility has also featured in the study of criticality, vulnerability and resilience. D'Este and Taylor (2003) consider that a network link is critical if its loss significantly diminishes the accessibility of the network or of particular nodes. This approach has been applied in studies at the strategic network level (Taylor et al., 2006; Kurauchi et al., 2009; García-Palomares et al., 2018; Ortega et al., 2020; Sarlas et al., 2020). Taylor et al. (2006) study vulnerability and identify the critical infrastructure in a network where the failure of any part of the transport infrastructure would have the most serious effects on the road system in the Australian National Transport Network. Sarlas et al. (2020) apply an attack-vulnerability approach to the resilience assessment of a transport network, selecting six indicators as sentinel variables, including four betweenness centrality accessibility measures. Other authors focus on removing a large number of sections in the network. Novak and Sullivan (2014) propose a measure that quantifies the relative importance of each link in a road network in terms of its system-wide contribution to emergency accessibility. Garcia-Palomares et al. (2018) evaluate the criticality of the road sections in Spain considering the disruption of 352 of these sections by calculating accessibility indicators. The tool provided by Ortega et al. (2020) not only addresses the criticality of elements in the transport network at a national scale, but also analyses the spatial coincidence of mid- to long-term changes in weather that may potentially affect the most critical stretches for the functionality of the network. Other authors relate transportation-infrastructure assets and improvements with the economic resilience of regions (Chacon-Hurtado et al., 2020). Östh et al. (2015) evaluate a resiliency capacity index and its relationship with a measure of accessibility to jobs in Sweden's municipalities, and conclude that socioeconomic resilience and accessibility are correlated in a nonlinear manner.

Most of the resilience analyses in the literature follow approaches based on link-removal simulations. According to Knoop et al. (2012), whatever the method selected, there are two general possibilities: either to simulate all possible blockages of links in a road network, or to pre-select potentially vulnerable links based on certain criteria and then analyse these links. This second approach involves three previous considerations: (i) the quality of the criteria for the preselection; (ii) the number of possible vulnerable links preselected, which should guarantee the inclusion of the most vulnerable links; (iii) and the degree of detail necessary for the analysis. In this paper, we propose a resilience evaluation framework that takes into account the considerations articulated by Knoop et al. (2012) in a planning context (Taylor et al., 2006; Jafino et al., 2021), where accessibility is recognized as an important variable (D`Este and Taylor, 2003). In particular, we measure the resilience of two transportation networks comparatively by monitoring the decline in overall territorial accessibility while subjecting the systems to the elimination of their sections, preselected in a set of elimination patterns which ensure the study of relevant links in an adequate level of detail at the planning stage. These patterns are based on relevant quality criteria: their criticality in terms of their contribution to territorial accessibility levels and potential damage from flooding. Section elimination has been applied in the literature to assess the resilience or remaining functionality of the road networks after severe disruptions. However, while previous studies have identified the criticality of each road section individually (one by one), in this work we propose a new framework to measure the resilience of transport networks built on the systematic calculation of accessibility indicators to study resilience at the regional scale, in which the sections are cumulatively eliminated in different simulations of severe disruptions from a comparative approach. Our framework is applied to analyse the road networks in two Mediterranean regions: Sardinia and Valencia. The climate conditions make the case studies particularly relevant due to the reported increase in the likelihood of extreme climate events such as flooding, which may cause disruptions to the transport networks (Miró et al., 2018; Autonomous Region of Sardinia, 2020).

3. Methodology

The resilience of the transportation network is assessed according to a two-stage methodology, as illustrated in Fig. 1. Stage 1 consists of preparing the geodatabases to define and select the mobility infrastructure sections, and Stage 2 includes the analysis of the resilience of these sections. Resilience is assessed by calculating the decline in the network's territorial accessibility, while its sections are simulated to be eliminated progressively and according to four elimination types (ETs). The resilience analysis includes recursively three steps: the definition of the sequence of section elimination, the generation of scenarios throughout the cumulative elimination of sections, and the calculation of accessibility. These calculations were performed in a GIS environment through ArcGIS 10.X.

The elimination of sections in the second stage is designed according to four elimination types that consider different kinds of loss (random and deterministic) and criticalities. One of the main consequences of climate change in the Mediterranean regions is the increase in extreme weather events such as torrential rains and floods, as can be seen in the reports of national (AEMET, 2020) and international organizations (MedECC, 2020). The effects of floods or torrential rain on a road could be similar to the elimination of a section, insofar as they can render a section unusable. Stage 1 consists of building a comprehensive geodatabase to feed the resilience assessment. This comparative study requires datasets to be compiled that describe the road network and the municipalities. The road network geodatabases include the arcs and attributes necessary to perform the accessibility calculations in each section. These attributes include the road type (motorway, dual carriageway, national, conventional and local roads) and its length and speed. The other dataset contains specific information on the centroids of the municipalities.

Stage 2 considers network resilience and studies the network's reaction to the cumulative elimination of road sections. This methodology is inspired by the work of Ortega et al. (2020), who calculated the criticality of the inland transport network in Spain, and invoked the concept of network resilience in terms of aggregated territorial accessibility. The assessment compares the accessibility results for a reference scenario 0 – the complete road network – to the results of a scenario *s*, denoting a network that lacks a certain number of sections that are simulated to be eliminated in a cumulative way. The aim of these simulations is to study the behaviour of the network in scenarios that are relevant for planning the adaptation of infrastructures to climate change. Resilience is studied using a measure of potential accessibility from the category of gravity indicators, which offers a compromise between complexity and interpretability (see Gutiérrez et al., 2011; López et al., 2008; Monzón et al., 2013; Ortega et al., 2012), as described in Equation (1):

$$PA_i = \sum_j \frac{P_j}{T_{ij}} \tag{1}$$

For each city origin i, its potential accessibility PA_i is calculated with respect to destinations j. P_j refers to the size – in this case, resident population – of each destination j, and T_{ij} is the generalised time a traveller takes to reach destination j from origin i along the network. The travel time is equal to the sum of the times of the arcs travelled along the minimum path according to Dijkstra's (1959) algorithm. A unique value of regional accessibility is then calculated as the average value weighted by the population, according to Equation (2):

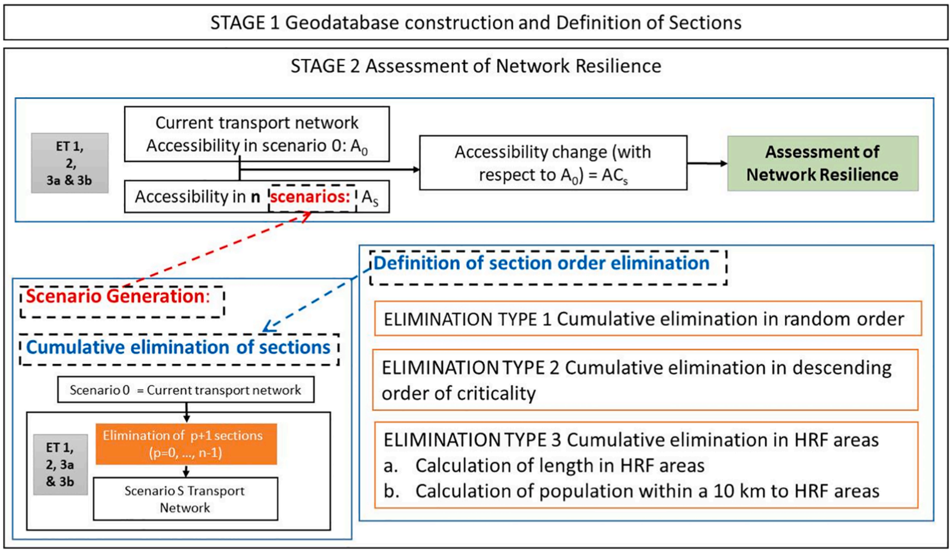


Fig. 1. Outline of the methodology.

$$A_s = \frac{\sum_i PA_i \bullet P_i}{\sum_i P_i} \quad (2)$$

For each ET, regional accessibility A_s is calculated for scenario 0 and different scenarios s. The difference between these values represents the percentage of decline in regional accessibility produced by the loss of network sections, according to Equation (3):

$$AC_s = \frac{A_0 - A_s}{A_0} * 100 \quad (3)$$

where, for each scenario s, AC_s is the percentage of accessibility change, A_0 is the indicator value for the reference scenario 0, and A_s is the indicator for scenario s. The elimination of even a few sections implies a loss of regional accessibility (ACs). The resilience of the transport network can be assessed by monitoring the interplay between the decline in AC_s and the number of sections eliminated. The higher the AC_s, the lower the resilience of the network. Different types of reaction – for example, varying decreases in regional accessibility – can be compared for each ET, when two or more regional transport networks are considered. The patterns of the elimination types (ETs) are described in Table 1.

Elimination type 1 (ET1) consists of removing sections following a random order. This ET simulates the occurrence of failures due to accidental events that randomly affect parts of the transport network, and was calculated as follows. First, ten random orders of elimination were created, and the process in Fig. 1 was repeated for each of these orders to obtain the accessibility value in each scenario. The final accessibility value A_s assigned to each scenario is the average of the values obtained after simulating the ten random orders. ET2 consists of the deterministic cancellation of the sections based on their criticality. According to some scholars (see Taylor et al., 2006), the criticality of a transport network element (either a link, such as a section; or a node, such as an intersection) can be defined as the damage associated to the removal of that element from the system. In this case, the damage is considered as the decrease in regional accessibility as stated above. Starting from the framework proposed and applied by Ortega et al. (2020), we assess the decline in regional accessibility corresponding to the removal of each section at a time (as illustrated in Fig. 2).

The method thus highlights how much single sections contribute to overall regional accessibility and – conversely – the potential damage associated to the elimination of these single elements. ET2 consists of removing the sections according to their ranking in terms of the differential regional accessibility decrease (from highest to lowest). We expect ET2 to produce the greatest losses of functionality, so it will serve as a reference to ensure a better understanding of the resilience of the networks (worst case scenario). ET3A and ET3B imply the removal of sections located in areas at high risk of flooding (HRF). Flooding is one of the main territorial hazards associated to extreme climate change-induced events. HRF areas are reported to be most likely to be affected by disasters due to flooding events. As the sections are removed deterministically, ET3A and ET3B differentiate according to the following two key variables: in ET3A, the removal affects the longest sections in HRF areas first, while in ET3B the spatial access to the infrastructure is modelled using a “coverage” approach, where service areas are calculated through buffer analysis in a particular network (Talen, 2003; Dony et al., 2015); the population residing within a specified distance from an infrastructure is considered to be “covered” by that infrastructure (Dony et al., 2015). In ET3B, cancellation affects first the “most useful” (i.e. with the largest potential catchment) sections. The key variable is the population residing in the service area, corresponding to the 10 km buffer of each section in the

Table 1
Elimination types: description, rationale, and mechanisms.

Code	Description	Rationale	Elimination pattern	Key variable
ET1	Cumulative elimination of sections in random order	This ET simulates specific accidents with a random behaviour, such as major storms, accidents, consequences of a lightning strike, etc. It also serves as a benchmark for comparison with the network resilience in the other two types of elimination.	Random	–
ET2	Cumulative elimination of sections in order of criticality	The accumulated removal of sections in descending order of criticality. Studying resilience in this way reveals the behaviour of the network when the most critical (i.e. associated to the greatest regional decrease in accessibility) sections are removed first. The results of this simulation can help plan preventive and adaptative efforts in the most critical sections.	Deterministic	Percentage of decline in regional accessibility
ET3A	Cumulative elimination of sections ordered by length, in areas with high risk of flooding (HFR)	The resilience of the network is studied assuming the elimination of the sections with the greatest likelihood of an extreme flooding event. The elimination priority is assumed to be the longer sections in HRF areas. The results of this simulation can help plan preventive and adaptative efforts on sections located in HRF areas.	Deterministic	Length of the section within HFR areas
ET3B	Cumulative elimination of sections in HFR areas ordered by the population in the section service area	The resilience of the network is studied assuming the elimination of the sections with the greatest likelihood of an extreme flooding event. In this case, the order of elimination prioritises the sections whose service area covers the largest population. The results of this simulation can help plan preventive, conservation and adaptive efforts on the sections with the largest population.	Deterministic	Population served by each section

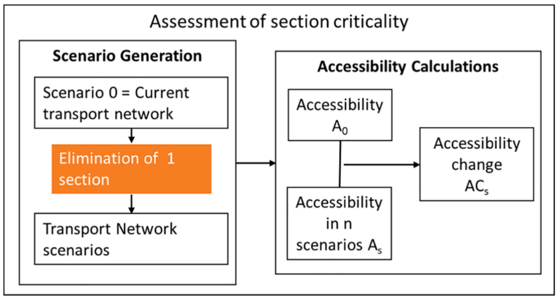


Fig. 2. Diagram of section criticality assessment.

network. If short distances are considered, there could be no population within the service area, and long distances could be less realistic because alternative route/sections could be found; the mid distance was therefore selected.

4. A case study in Sardinia (Italy) and Region of Valencia (Spain)

We apply the methodology to the assessment of the comparative resilience of the transport (road) systems in two Mediterranean regions: Sardinia, Italy, and Valencia, Spain (Fig. 3).

The region of Sardinia in the Mediterranean basin is the second largest Italian island and has an area of about 24,100 km^2 and a population of about 1.6 million inhabitants (Italian National Institute of Statistics, 2018). In the period 1951–1999, the average yearly minimum temperature in Sardinia was in the range of 7.2–14.6 °C, the average maximum temperature was 15.6–22.7 °C, and the average yearly precipitation was 414–1118.9 mm (Autonomous Region of Sardinia, 2019). Summers are hot and dry, while winters are mild and somewhat rainy (Lai et al., 2020). The wettest months are November and December, while rain is rare or non-existent in July and August (Autonomous Region of Sardinia, 2016). In October 1951, torrential rain fell for 70–80 h in Sardinia, triggering serious

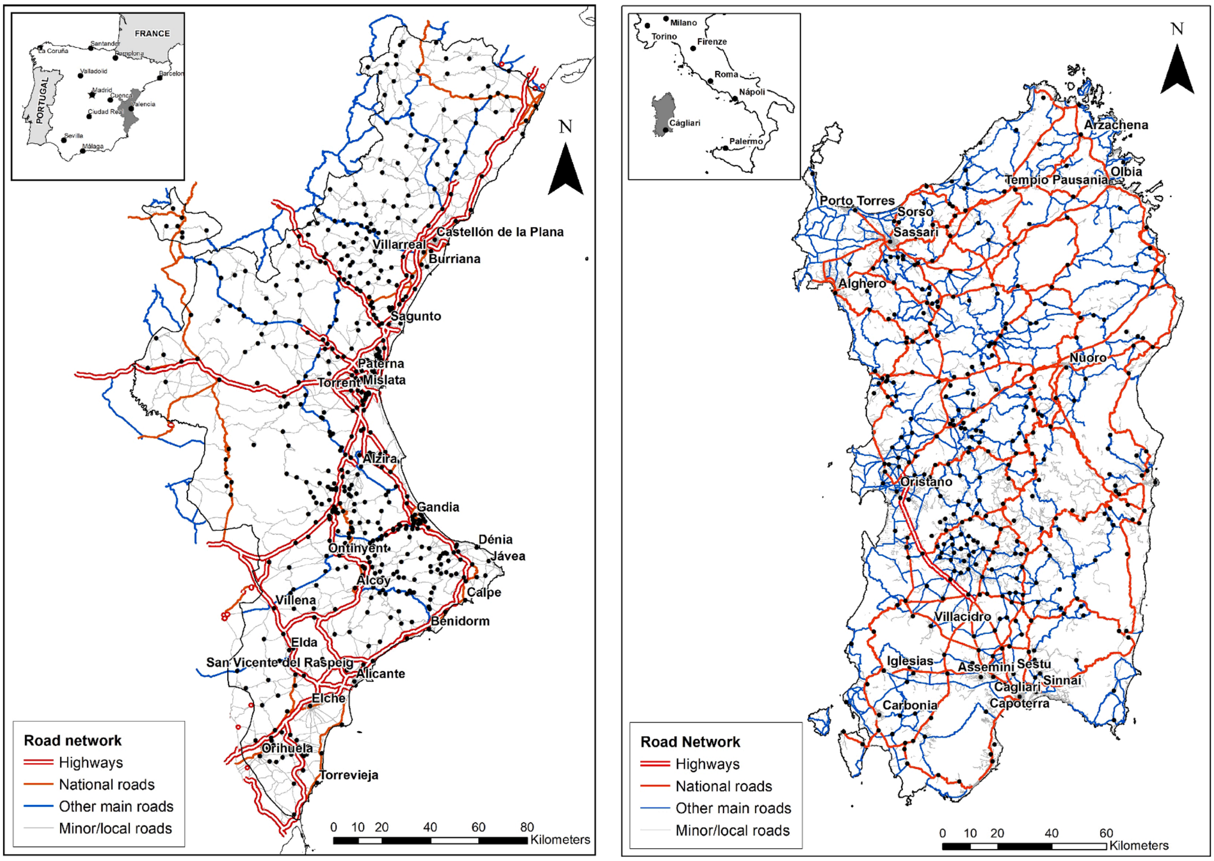


Fig. 3. Road networks. Left: Region of Valencia (Spain). Right: Sardinia (Italy).

flooding (Pinna and Grava, 2016). The rainfall affected about 8,000 square kilometres and caused the collapse of several buildings and bridges, and the definitive abandonment of population centres (De Montis et al., 2015; Pinna and Grava, 2016). The region of Sardinia belongs to one of the most vulnerable areas in Europe in terms of climate change (Italian Ministry of the Environment and Protection of Land and Sea, 2015a,b; Ledda et al., 2020). According to the Autonomous Region of Sardinia (2020), the main impacts in the region deriving from climate change include (i) the increase in extreme weather events, erosion and coastline retreat, and (ii) rising sea levels. In 2013, the region of Sardinia experienced extreme rainfall (De Maio et al., 2014) due to Cyclone Cleopatra, and severe overflowing of the rivers in part of the region (Beretta et al., 2018). The consequences of this event led to the death of 18 people around the region (Autonomous Region of Sardinia, 2014). Cyclone Cleopatra caused extensive damage to transport and mobility infrastructures, including the collapse of bridges on provincial roads no. 46, 24 and 38bis (Autonomous Region of Sardinia, 2014; EDI-CEM, 2015; Autonomous Region of Sardinia, 2017, 2017a). Although over the years, some bridges have been restored, restoration measures have not yet been completed for some other strategic bridges (Autonomous Region of Sardinia, 2020a; Autonomous Region of Sardinia, 2020b). Finally, in the last week of November 2020, serious rainfall affected eastern Sardinia: three people died, and several roads, including national roads no. 126, 129 and 131dcn – one of the most important in terms of vehicular traffic flows – were interrupted by floods and landslides, and a bridge collapsed (Autonomous Region of Sardinia, 2020c; La Nuova Sardegna, 2020).

The Region of Valencia is located on the east coast of the Iberian Peninsula. It has 5,003,769 inhabitants (INE, 2019), and is the fourth most populous Spanish region. It has a total area of 23,255 km^2 and a typically Mediterranean landscape. The climate in the region is semi-arid Mediterranean with an average annual rainfall ranging from 300 to over 1000 mm, with the characteristic Mediterranean seasonal rainfall distribution consisting of a summer drought and two wet periods in autumn and spring. There is also episodic heavy rainfall in summer and autumn, which may account for a large proportion of the annual precipitation (Amengual et al., 2017). This region has already recorded decreases in moderate rainfall since the 1980s attributed to climate change. Water shortage and drought and their consequences are also expected to rise in the coming decades (Daniell et al., 2011), and there has been an increase in extreme torrential rainfall in basins located in the region (Miró et al., 2018).

The geodatabases used in the resilience assessment described in Section 3 have the following characteristics. The road networks are topologically correct, with a very high level of detail – they include motorways, dual carriageways, national, conventional and local roads – and a precision of less than 100 m (sources are the Autonomous Region of Sardinia for the Sardinian road network, updated in 2014, and the Instituto Cartográfico Valenciano for the Valencian network, updated in 2019). Accessibility calculations also require one geodatabase for each region that includes the centroid of each municipality (NUTS 4) and its population. The Region of Valencia has 542 municipalities and Sardinia 377. Table 2 summarizes the relevant characteristics of the geodatabases used in the case study.

The selection of the sections of the transport networks to be eliminated is crucial, since the ETs and the calculation of the related variable will affect these sets of sections for each region. The road network geodatabases include all roads – motorways, dual carriageways, national, conventional and local roads – but only some are selected for elimination. The types of roads included in this selection are national or provincial main roads for Sardinia, and highways and national roads for Valencia. The selected road types are divided into these sections, when there is an intersection with another road; hence 78 sections were selected from the whole road network for Sardinia and 74 for Valencia. Sections of minor road types are not considered in this selection, as their elimination has a very low impact – i.e. it produces negligible changes in regional accessibility – on the road network as a whole.

By implementing the methodology for the assessment of comparative resilience, accessibility values were obtained for each of the 377 municipalities in Sardinia and the 542 municipalities in the Autonomous Region of Valencia. The accessibility calculations were made using a GIS-based network accessibility analysis toolbox named TITIM-GIStool (Ortega et al., 2014). In ET3B, the service area of each section is calculated using the service area function of the ArcMap 10.x Network Analyst extension. For Sardinia, we selected the areas in the first category of hydrogeological risk (Ri4) as HRF areas, according to the dataset maintained by the Regional Agency of the Hydrographic District of Sardinia, Autonomous Region of Sardinia. In the Autonomous Region of Valencia these areas are restricted to areas in categories 1 and 2 in the map of PATRICOVA (Direcció general d'ordenació del territori, urbanisme i paisatge, 2005).

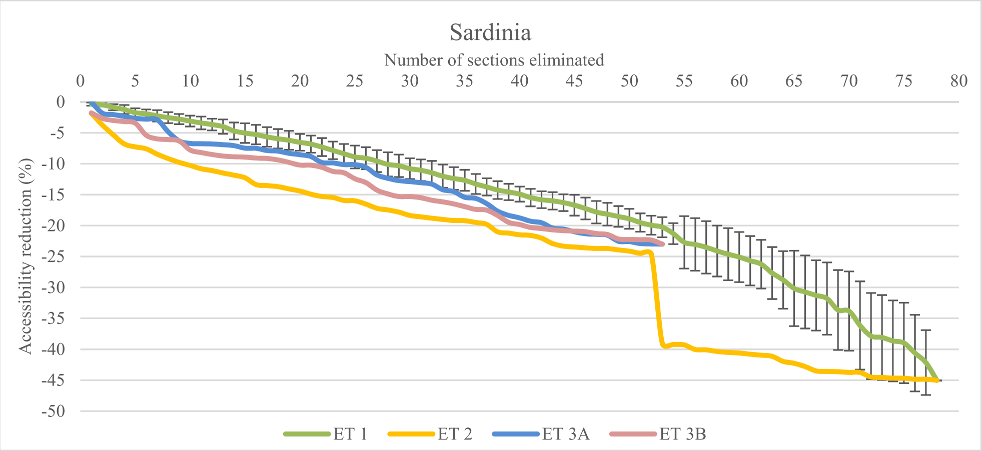
5. Results

This section reports on the results of our exercise. Fig. 4 shows the percentage of decline in overall accessibility (*ACs*) for the two regions versus the number of sections removed according to different ETs.

The results show that the two regions react similarly to the various causes of disturbance to the road system, as simulated by the ETs. In both territories, the removal of sections according to ET1, i.e. randomly, causes the lowest loss of accessibility; ET3A and ET3B (deterministic elimination of sections in HRF areas) lead to an intermediate loss of accessibility; while ET2 (deterministic elimination of sections by criticality) causes the highest loss of accessibility. Major damage can be expected from the ET2 elimination model, as the

Table 2
Main characteristics of the geodatabases.

Region	Municipalities	Population			Road length (km)	Road types considered for the elimination of sections and length (km)	Sections
		Total	Average municipal	Standard deviation			
Valencia	542	4,963,703	9,158	40,152.5	39,500	Highways and national roads (10,300)	74
Sardinia	377	1,628,171	4,376	12,236.9	26,000	National roads and main provincial roads (2,900)	78



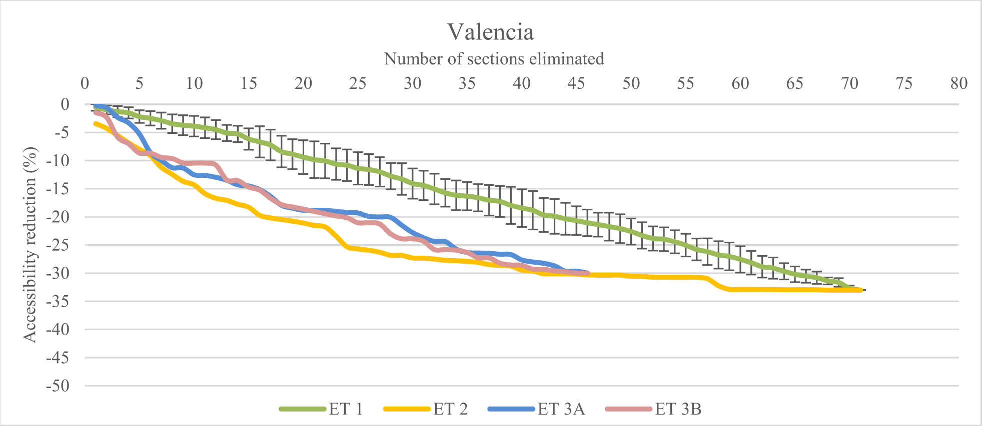


Fig. 4. Analysis of the comparative resilience of the road networks in Sardinia (top) and Valencia (bottom). The percentage of decline in regional accessibility is mapped versus the number of sections removed according to various ETs. For ET1, interval values represent the standard deviation of the ten random scenarios.

most critical sections in the network – i.e. with the largest associated loss of accessibility – are simulated to be eliminated first. For this reason, the scenarios generated after eliminating the most critical sections were expected to produce the worst-case scenarios in terms of global accessibility loss.

The results show a different response *ceteris paribus* – i.e. with the same ET – for the two regional road networks. As seen in Fig. 5, the percentage of decline in regional accessibility for each ET is higher for Valencia than for Sardinia, pointing to the greater resilience of the Sardinian road network, at least until the elimination of the 53rd section. This is apparently a paradox: the Sardinian system has a lower quality and capacity, but is more homogeneous and denser than the Valencian system, which relies more on large (and more critical) infrastructures.

In the case of Valencia, ET2 and ET3B produce similar accessibility decreases when three to five sections are removed. Special attention should be paid to sections in which two situations converge; these are key elements in the region's accessibility and are in an area where extreme climate events are likely to occur.

The results suggest the individuation of key threshold values for the resilience of the systems (see Figs. 4 and 5). In the case of Sardinia, the elimination of 53 sections (67.90% of the total network) causes a significant decline in accessibility according to ET2 and an increase in dispersion in ET1. This represents a collapse and indicates that the resilience of the Sardinian road network has its critical limit when this elimination threshold is reached. There are other minor transitions for ET3A at 15.09% of the total network eliminated, and ET3B at 11.32% of the total network eliminated. The Valencian system does not experience any loss of accessibility similar to the case of Sardinia under ET2. The Valencian system shows a few pronounced changes associated to the removal of 1.41% of the total network eliminated according to ET2, 13.04% of the total network eliminated according to ET3A, and 6.52% of the total network eliminated according to ET3B. Additionally, the dispersion of accessibility values under ET1 is more regular for Valencia than for Sardinia.

The results also reveal the impact of removing sequences of sections. Table 3 shows the road sections in the highest decile of accessibility loss for each ET: for Valencia, sections 43 and 46, and, for Sardinia, 11, 48, and 67. These kinds of crucial road sections are not evenly spatially distributed (Fig. 6).

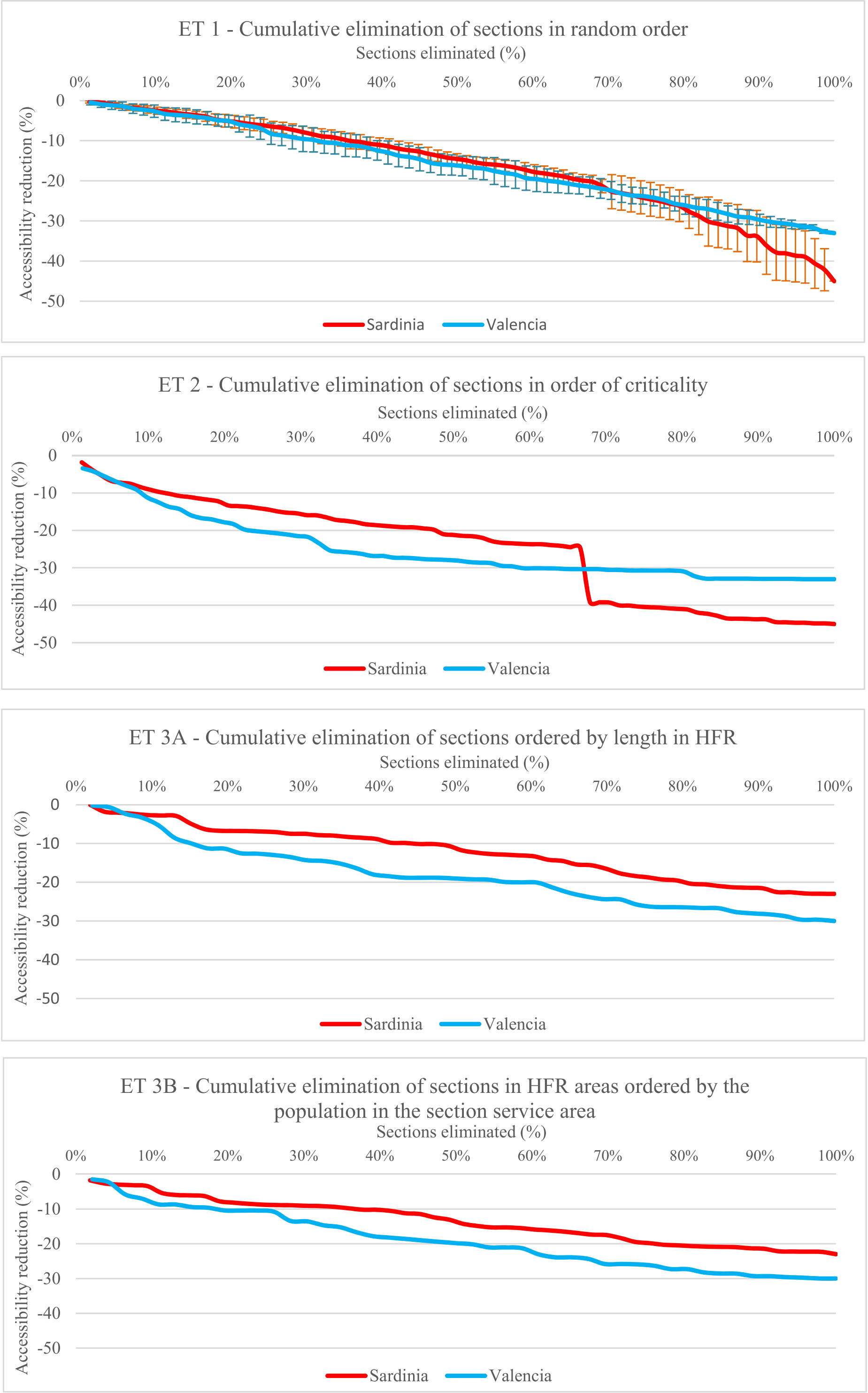


Fig. 5. Detailed comparative resilience analysis of the road networks in Sardinia (red line) and Valencia (blue line). The percentual decline in regional accessibility is mapped versus the percentage of sections removed according to various ETs. For ET1, interval values correspond to the standard deviation of ten random scenarios. Valencia sections (74) and Sardinia sections (78) are shown homogenized on the horizontal axis using interpolation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Road sections in the highest decile of accessibility loss, by region and ET. Accessibility losses in the highest decile are marked in bold.

	Road section	Length (km)	ET 2			ET 3A			ET 3B		
			Order	Sections eliminated (%)	Accessibility loss	Order	Sections eliminated (%)	Accessibility loss	Order	Sections eliminated (%)	Accessibility loss
Valencia	5	50.51	3	4.23	−1.293						
	11	40.73	11	15.49	−1.560	18	39.13	−1.589			
	14	159.92							5	10.87	−1.657
	43	**76.14**	**1**	**1.41**	**−3.437**	**6**	**13.04**	**−3.281**	**3**	**6.52**	**−3.497**
	46	**96.14**	**7**	**9.86**	**−2.084**	**3**	**6.52**	**−1.697**	**13**	**28.26**	**−2.651**
	50	34.88	16	22.54	−1.435						
	54	83.85	24	33.80	−1.880						
	56	67.77	23	32.39	−1.642						
	60	48.74				5	10.87	−1.998			
	61	68.69							28	60.87	−1.761
Sardinia	4	35.43	38	48.72	−1.200						
	11	**30.40**	**2**	**2.56**	**−1.871**	**2**	**3.77**	**−1.766**	**1**	**1.89**	**−1.766**
	23	7.78	53	67.95	−14.451						
	25	103.72	16	20.51	−1.090				39	73.58	−1.100
	48	**42.76**	**1**	**1.28**	**−1.855**	**8**	**15.09**	**−1.951**	**6**	**11.32**	**−1.965**
	54	89.81				27	50.94	−1.223			
	59	31.91				38	71.70	−1.220	27	50.94	−1.212
	67	**42.23**	**4**	**5.13**	**−1.465**	**9**	**16.98**	**−1.469**	**10**	**18.87**	**−1.461**
	71	27.84	3	3.85	−1.609						

6. Discussion

This section includes a discussion of the most significant outcomes of this exercise. Firstly, the evidence shows that the two regional road networks react similarly to the different ETs. The decrease in accessibility is lowest under ET1 (random removal), and highest under ET2 (deterministic elimination of the most critical sections). This result has important implications for transport planning in areas such as interventions in road maintenance, as preventive or adaptative tasks must be undertaken based on technical criteria in order to take efficient decisions. Intermediate values are obtained for ET3A and ET3B (elimination of sections in HRF areas). In both cases, damage caused by climate change (i.e. flooding) is visibly lower than the fatal effects connected to the targeted cancellation of the most critical sections. There are some differences in the two reaction patterns that depend on the geography of the systems and the road hierarchy. This leads to the second outcome of the study. The road network in Valencia is less resilient than in Sardinia for all ETs, despite its evidently higher quality in terms of the size and capacity of the road sections. This paradox can be explained by the fact that hierarchical and sparse road networks (such as the Valencian network) are less resilient than dense homogeneous networks, which offer travellers more shortcuts. In the first kind of systems, the collapse of a major section is much more harmful for the whole of the transport and mobility system. Thirdly, the pattern of accessibility reduction is gradual, with the exception of the sharp decline in the 53rd section for the Sardinian network. This threshold clearly indicates a collapse situation that should be avoided. This section corresponds to section 23 in our study, located in southern Sardinia and connecting Samassi with Villasor (road SS196dir) (see Fig. 6). It is not especially relevant in the Sardinian network as a whole, and the isolated collapse of this section could be partially resolved by other nearby main roads. However, the prior failure of these other roads has led to a highly weakened system, which ultimately collapses with the removal of this section. Thus the cumulative effect of the collapse of several sections causes a sharp decline in accessibility levels rather than the collapse of specific sections. As a fourth outcome, the assessment can point to important sections in the highest decile of loss of accessibility of the road network. In Valencia, these road sections are clustered around the major city of Valencia and in Sardinia they are located around the main metropolitan area of Cagliari; they are part of the corridors that connect other important cities with these two most populated cities, and thus have an important effect on the road transport system as a whole. Specifically, it is worth citing sections 43 and 46 for the Valencian network; these sections belong to the corridor that connects the city of Valencia with large coastal cities in the south such as Gandia and Benidorm. Section 43 is also part of the connection with Alicante (the second largest city in the autonomous region of Valencia) through the inland corridor. In the Sardinian network, sections 11 and

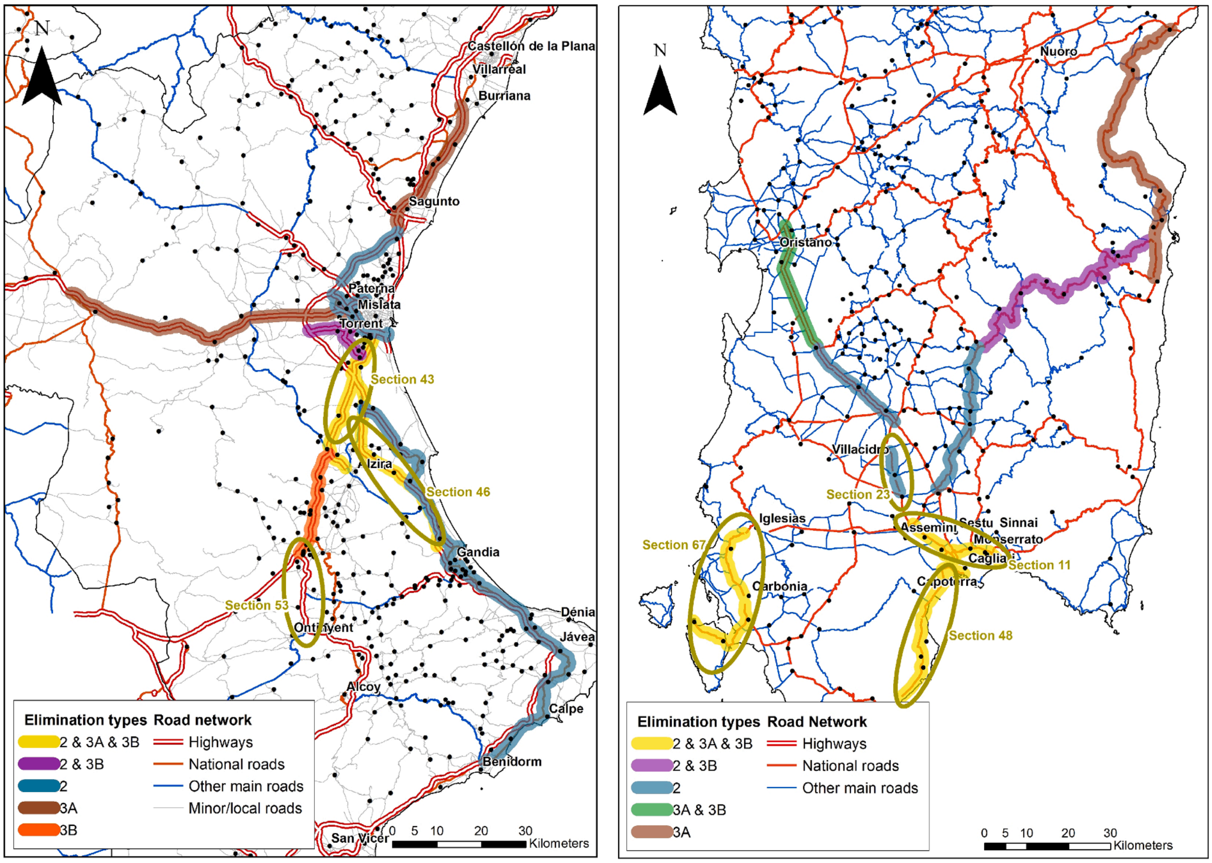


Fig. 6. Spatial analysis of the most critical road sections (in the highest decile of associated loss of accessibility) by ET in Valencia (left) and Sardinia (right).

48 connect Cagliari with the north and south respectively, and the loss of this connection between the cities and Cagliari implies high levels of accessibility loss. The same also holds for other sections located far from these two main cities. The scale of the impact on the road transport system as a whole depends on the existence of an alternative route. Section 67 in the Sardinian network has no satisfactory alternative, so eliminating it would cause significant damage to the whole system. Conversely, removing section 53 (highway) for the Valencian network implies less than 0.5% of accessibility loss as it has an alternative national road that mitigates the negative effects.

7. Conclusions

This section presents the final considerations on this work and our critical answers to the framework described in the introduction. Although the resilience of transport networks has been studied from various points of view, very little research has been done on the loss of network functionality in a quantitative way (Gu et al., 2020a,b) at the regional level. Authors such as Taylor et al. (2006), Garcia-Palomares et al. (2018) and Ortega et al. (2020) have studied criticality/vulnerability in terms of loss of accessibility by eliminating sections one by one, but not cumulatively. Akbarzadeh et al. (2019) consider this cumulative elimination according to their importance but at an urban level, and does not compare three types of elimination. We also calibrate the assessment framework to consider the effects of climate change, thus providing analysts and decision-makers with an accurate indication of the most fragile sections of the road networks and serving as a basis for the location of specific defensive and preventive actions.

With respect to the possibility of building a framework for the comparative assessment of resilience, we have built a methodology to compare the capacity of different road networks to withstand, self-organize and react to severe conditions. The display of the results in a single chart clearly shows the reaction of the regional road networks analysed under different ETs. This powerful framework vividly and effectively portrays the pattern of efficiency reduction and highlights the most critical sections in the systems in question. This exercise offers a way to model system resilience along a cumulative process of section removal. The framework can detect key thresholds corresponding to irreversible collapses, and can be used as a support system for designing and planning transport policy. The results confirm the outcomes of other studies on network resilience (Berche et al., 2009; Caschili et al., 2015; De Montis et al., 2016 and 2019), since the greatest damage derives from the deterministic elimination of the most critical elements, while the least damage is associated with random removal processes. This corresponds to an intuitive consideration: the removal of highly crucial sections first leads to massive damage and disruption in the transportation system.

We have demonstrated that the damage associated to the removal of sections can be very effectively proxied by the concept of accessibility, in line with previous studies (D'Este and Taylor 2003; Taylor et al., 2006; García-Palomares et al., 2018; Ortega et al., 2020). Loss of accessibility is an efficient gauge of infrastructure malfunction; and conversely, the framework allows the residual accessibility level of a road network to be monitored when it is subject to different patterns of attack. We have again demonstrated the highly flexible and overarching nature of the concept of territorial accessibility, as an aggregated measure of the service quality of a transportation network. Our approach has been applied successfully to investigate two regional networks located in very different contexts. However, the roads considered in the context of each region are functionally similar for each road type within each region, so network resilience could be addressed in both case studies separately. A comparative approach could be applied to these two case studies thanks to the adoption of a proper impact measure, i.e. the percentage accessibility loss triggered by the elimination of certain sections.

Finally, with respect to the interplay between resilience assessment and adaptation to the effects of climate change, our aim was to create a framework that is able to integrate the hydrogeological risk into the drivers and causes of disfunction or the total blockage of a section. ET3A and ET3B are deterministic patterns of section removal, according to their officially documented flood risk. We have demonstrated that these ETs cause intermediate damage to the road networks of a similar order for the two regions. Monitoring accessibility reduction allows the most fragile sections of the systems in question to be located, so policies can be implemented to counteract and anticipate fatal events through the adequate rebuilding and reinforcement actions. Although this work has satisfactorily achieved its objectives, its limitations open up opportunities for future research. The first is that this work is restricted to regional boundaries, and the accessibility calculations consider the origins and networks within the regions under study. This approach does not therefore take into account transregional or transnational accessibility. We have also restricted the study to the road network; further work could be enriched by expanding the origins and networks beyond the regional boundaries, considering roads and railways as an interconnected and multimodal service. In the case of Sardinia, as it is an island, the road network is complete and within its administrative limits. An expansion of this network should consider other modes such as air or maritime transport. Another limitation derives from the databases available for the calculations, which correspond to the current situation of HRF areas, roads and population reported by the public administrations. Traffic intensity data are unavailable for the two regions considered, and the population residing in the service area is used as a proxy in ET3B. The traffic intensity values or a different distance for the service area could have slightly modified the prioritisation of the elimination of sections. In the present context of climate change, future research would benefit from forecasts of climate variables and infrastructure improvements.

We contribute to the literature with a framework on a regional scale that enables the assessment of the resilience of transport networks, assuming four section ETs, where sections are removed randomly or deterministically. A new research opportunity emerges from the definition of the ETs. Deterministic ETs are designed as elimination patterns that could be caused by an extreme climate event, and a key variable is used to prioritise the elimination, which is related to the functionality of the section in the network. ET2·considers the criticality of the sections that could be eliminated by an extreme climate event, i.e. we do not distinguish among climate events or the likelihood of their occurrence, and we take into account the functionality of the network in terms of potential accessibility. In ET3A and ET3B, we consider areas with a high flood risk and the section length and population served by each section as the variables related to the section function. Further work could expand the interest of this approach for adaptation to climate change by designing elimination types that consider other variables such as elevation or distance to water. A more detailed study on the physical characteristics of the infrastructure (such as slope geotechnics or drainage service levels) would improve the deterministic ETs, as the prioritization of the sections to be removed could also be based on the stretches that are most likely to fail.

Acknowledgements

This research was initiated while the first author was visiting at University of Sassari. The authors are grateful by the hospitality of the University during Dr. Martin's visit. The authors wish to acknowledge the financial support of the "2018 Visiting Professor Programme at the University of Sassari" for the grant awarded to Belén Martín. This paper was produced under the framework of the project "Estudio de la criticidad de las infraestructuras de transporte en el contexto de los efectos del cambio climático", funded by Universidad Politécnica de Madrid , research project no. P1913200085. The authors would also like to thank the four anonymous reviewers for their comments and suggestions to improve the manuscript.

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